^{17}O burning rate in star: a revision

Carlo Gustavino – INFN Roma

on behalf of the LUNA CNO Working group

CNO cycle

Sun: ~15 MK
AGB:~30-100 MK
Massive Stars: ~ 100 MK
Novae~100-400 MK

- **StarLib Database**
- **New CNO data from LUNA**

  $^{14}N(p,\gamma)^{15}O$ - $^{15}N(p,\gamma)^{16}O$ - $^{17}O(p,\gamma)^{18}F$

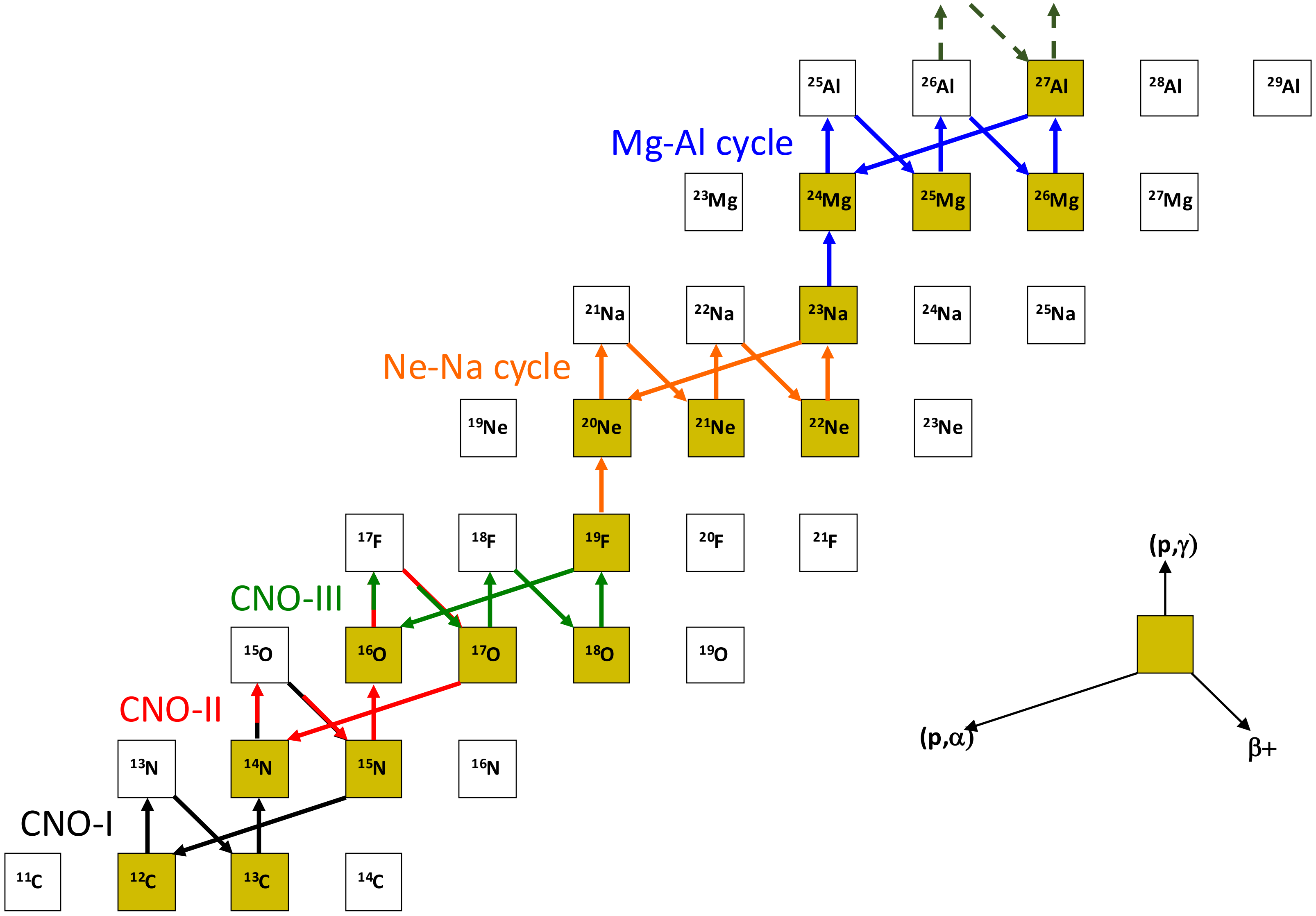
  $^{17}O(p,\alpha)^{14}N$ - $^{18}O(p,\gamma)^{19}F$ - $^{18}O(p,\alpha)^{15}N$

  $^{12}C(p,\gamma)$, $^{13}C(p,\gamma)$, $^{16}O(p,\gamma)$
- **R-Matrix Formalism**

  -Accurate (multi-level Breit-Wiegner)

  -It include interference and DC effects

  AZURE2 open access code



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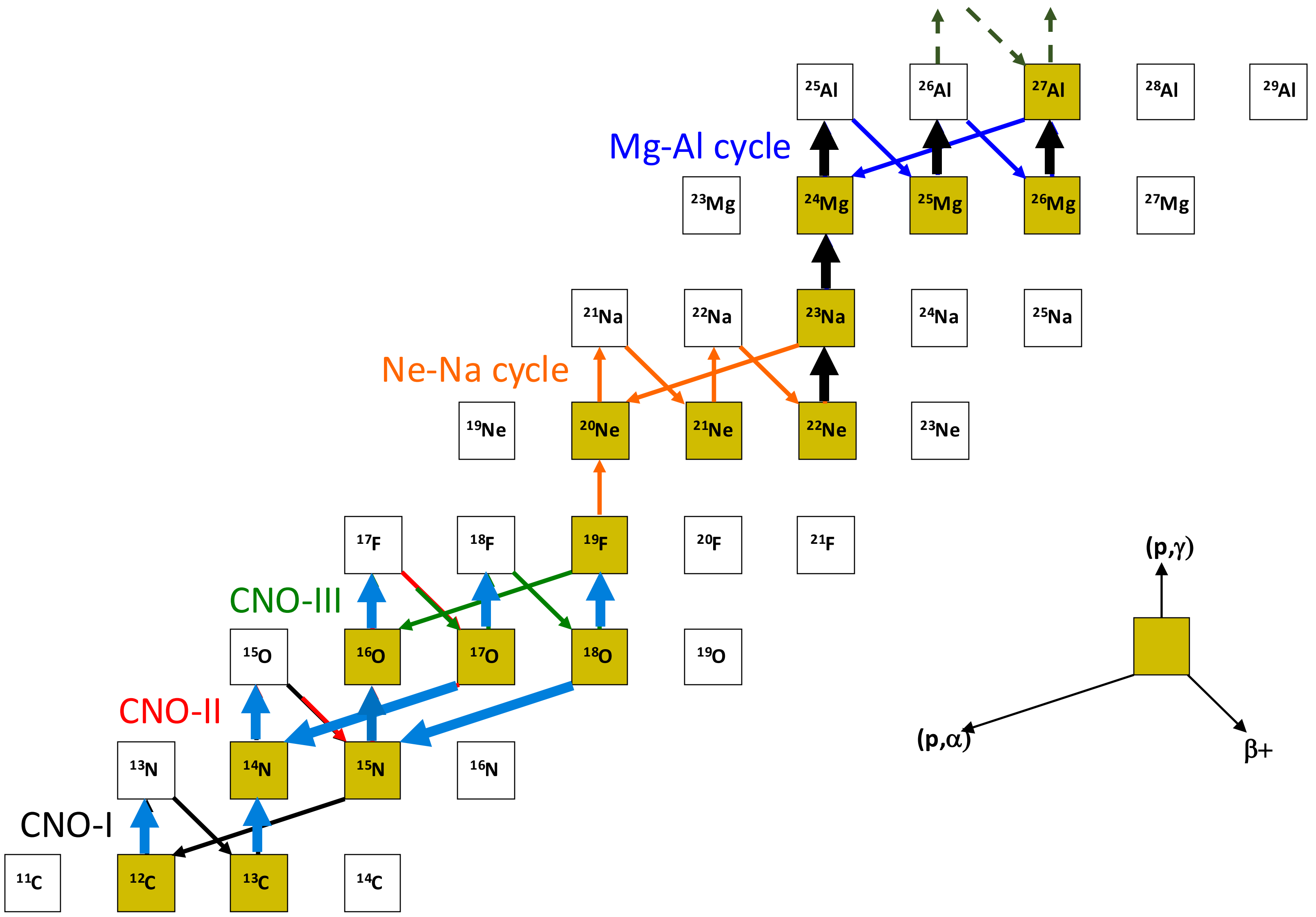
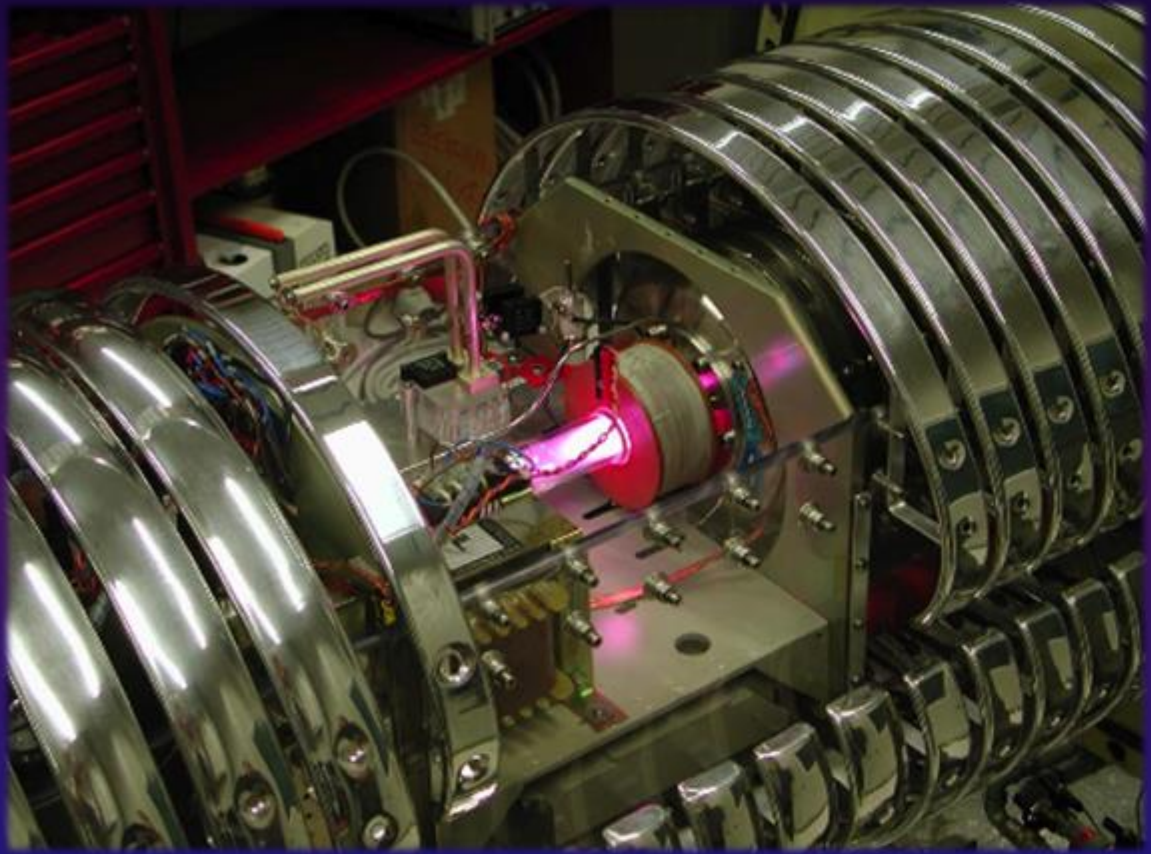


Gran Sasso Laboratory (LNGS)

Background reduction with respect to Earth's surface:
$\mu \sim 10^{-6}$
$\gamma \sim 10^{-2}$-10^{-5}
neutrons $\sim 10^{-3}$

LUNA 400



$E_{beam} \approx 50 – 400$ keV
$I_{max} \approx 300\ \mu A$ protons,^4He
Energy spread ≈ 70 eV

$^{14}N(p,\gamma)^{15}O$	(Sun,CNO-I cycle)
$^3He(^4He,\gamma)^7Be$	(Sun, BBN)
$^{25}Mg(p,\gamma)^{26}Al$	(Mg-Al Cycle)
$^{15}N(p,\gamma)^{16}O$	(CNO-II Cycle)
$^{17}O(p,\gamma)^{18}F$	(CNO-III Cycle)
$^2H(^4He,\gamma)^6Li$	(BBN)
$^{22}Ne(p,\gamma)^{23}Na$	(Ne-Na Cycle)
$^2H(p,\gamma)^3He$	(BBN)
$^{13}C(\alpha,n)^{16}O$	(s-process)
$^{12,13}C(p,\gamma)^{13,14}N$	($^{12}C/^{13}C$ ratio)
$^{22}Ne(\alpha,\gamma)^{23}Na$	(s-process)

Astro Motivations

<u>AGB stars</u>: mixing mechanisms and isotopic composition $^{16}O/^{17}O$ (atmosphere and extrasolar grains)
<u>Novae explosions</u>: influences ^{19}F and ^{15}N abundances as measured in pre-solar grains and satellite observations of $^{18}F(\beta^+,\nu)^{18}O$

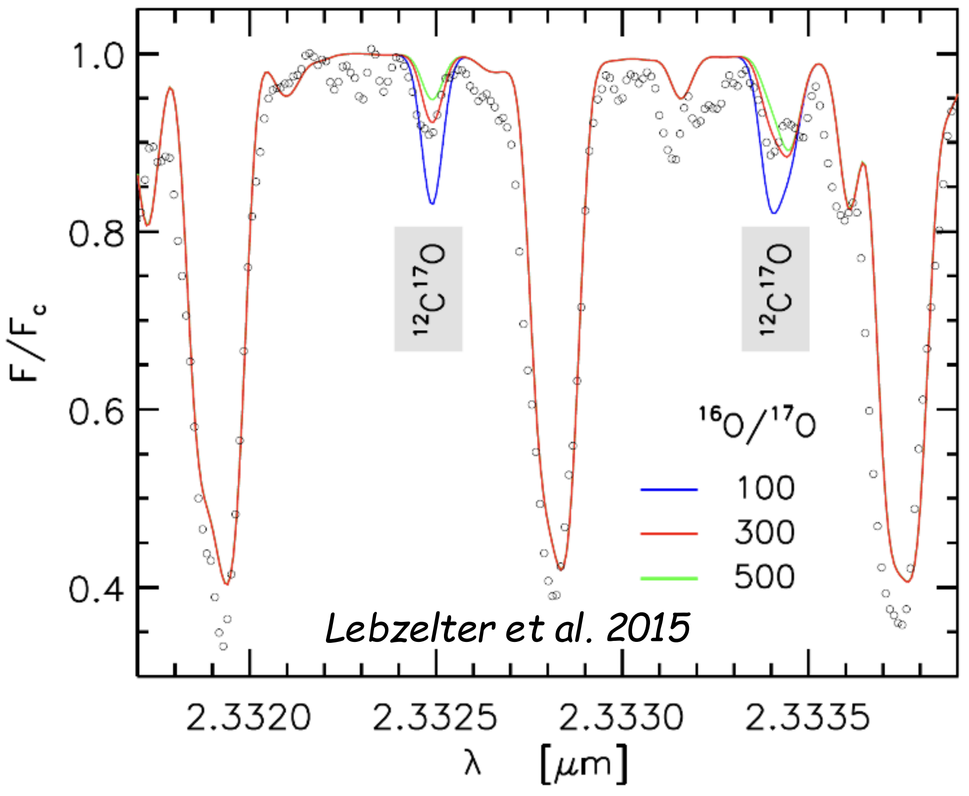


Fig. 1. Observed spectrum of HD 27292 (dots) showing two $^{12}C^{17}O$ lines. The three synthetic spectra (solid lines) are for T_{eff}=4000 K and $\log g$=1.5 with $^{16}O/^{17}O$=100, 300, and 500.

Procedure

1. Poles fit
2. S Factor evaluation
3. Reaction rate calculation

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Data Literature

- Resonant parameters
  * "Charged-particle thermonuclear reaction rates" Longland, Iliadis et al. 2010 Nuclear Physics A 841
  * more recent works
  * Tilley et. al 1995 Nuclear Physics A595 (or similar)
- Cross section
  * everything available

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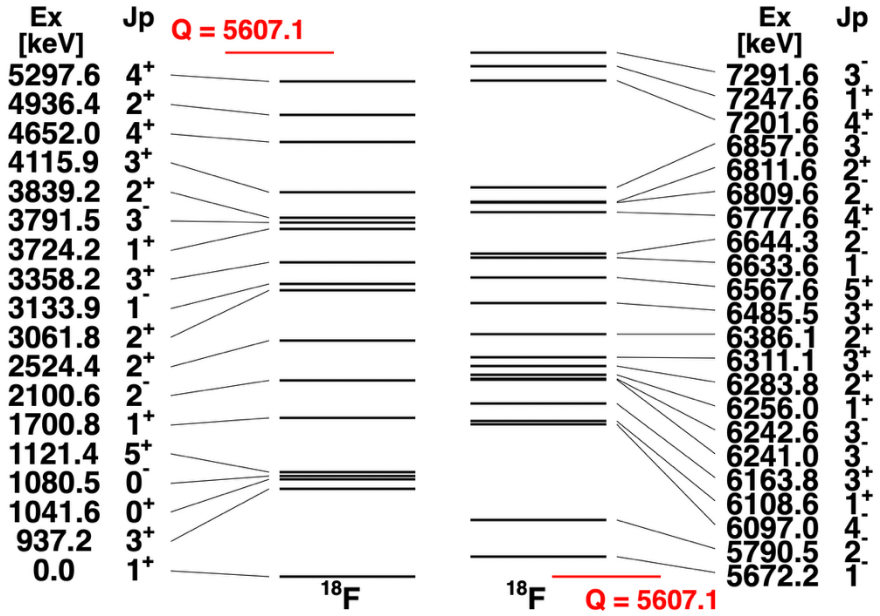
AZURE2

- multi-channel – (p,γ) and (p,α) or (p,p)
- multi-level: states up to 2 GK, high energy poles, relevant subthreshold states – here for primary γ-rays
- fit - poles widths most probable value and uncertainty DC, low energy tail of higher energies resonances and interference included



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recently directly measured in LUNA: 30(6) neV
Gesue et al. 2024 PRL 133, 052701

E_{cm} [keV]	E_x [keV]	$\omega\gamma$ [eV]	J^π	Γ_p [eV]	Γ_α [eV]	Γ_γ [eV]
64.48(54)	5671.6(2)	$2.95(60)\times10^{-11}$	1^-	$3.50(68)\times10^{-8}$	130(5)	0.44(2)
182.73(58)	5789.9(3)	$1.66(12)\times10^{-6}$	2^-	$4.00(24)\times10^{-3}$	13.3(5.5)	$1.1(3)\times10^{-2}$
489.3(1.2)	6096.4(1.1)		4^-	138(26)	106(17)	$3.07(50)\times10^{-2}$
500.9(3.0)	6108(3)		1^+	0.20(2)	33.6(3.3)	0
529.4(6)	6136.5(3)	0.110(25)				
556.1(1.0)	6163.2(9)		3^+	140074(257)	5.0(6)	0.595(134)
633.3(9)	6240.4(8)	0.16(26)	3^-	58.2(7.0)	133(24)	0
634.9(3.0)	6242(3)		3^-	40.8(3.7)	137(35)	0.73(11)
654.9(2.6)	6262.0(2.5)		1^+	27(3)	575(120)	0
676.1(1.0)	6283.2(9)		2^+	11121(186)	28.1(5.0)	0.603(29)
703.4(9)	6310.5(8)		3^+	525(117)	426(82)	0.17(4)
778.4(1.8)	6385.5(1.7)		2^+	109(11)	286(87)	0.270(68)
877.8(1.6)	6484.9(1.5)	$1.93(17)\times10^{-2}$	3^+	277(91)	123(25)	0
959.9(1.6)	6567.0(1.5)		5^+	1.2(1)	560(132)	$2.6(5)\times10^{-2}$
1026(10)	6633(10)		1^-	2920(315)	77090(2000)	0
1036.6(9)	6643.7(8)	0.275(28)	2^-	368(61)	231(40)	0
1169.9(1.5)	6777.0(1.4)		4^+	9000(1000)	150(24)	0.31(8)
1196.0(1.6)	6803.1(1.5)	$2.70(92)\times10^{-2}$				
1201.9(5.0)	6809(5)		2^-	16570(1600)	71500(2000)	0
1203.9(7.5*)	6811(7.5*)		2^+	2750(450)	210(67)	0
1250(10)	6857(10)		3^-	5000(1000)	30(7)	0
1270.3(1.8)	6877.4(1.7)	$5.0(1.9)\times10^{-2}$				
1593.9(2.1)	7201(2)		4^+	29400(1000)	500(58)	0
1639.9(2.1)	7247(2)		1^+	5000(1000)	55000(5000)	0
1683.4(2.1)	7291(2)		3^+	15820(1426)	44180(15000)	0

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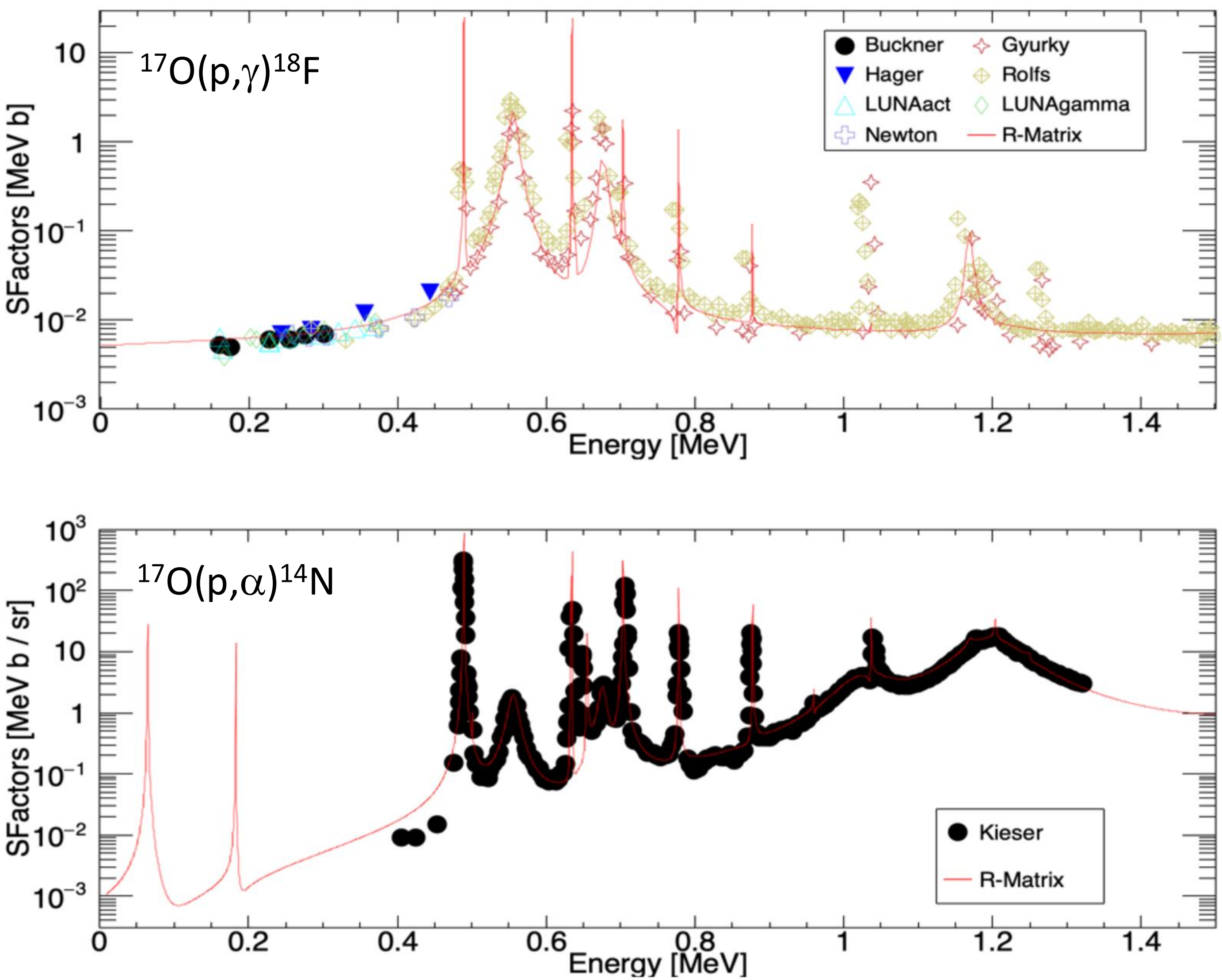

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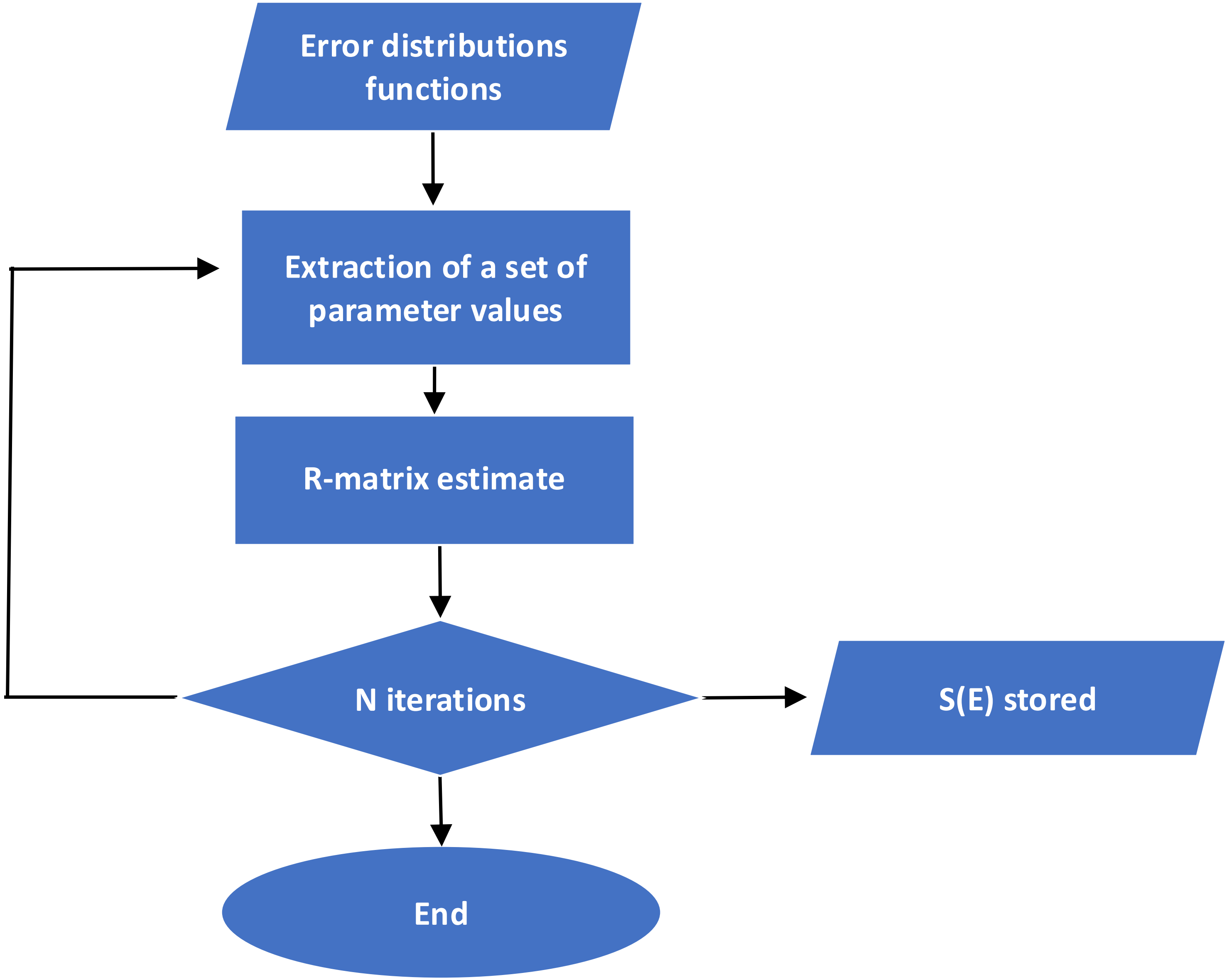

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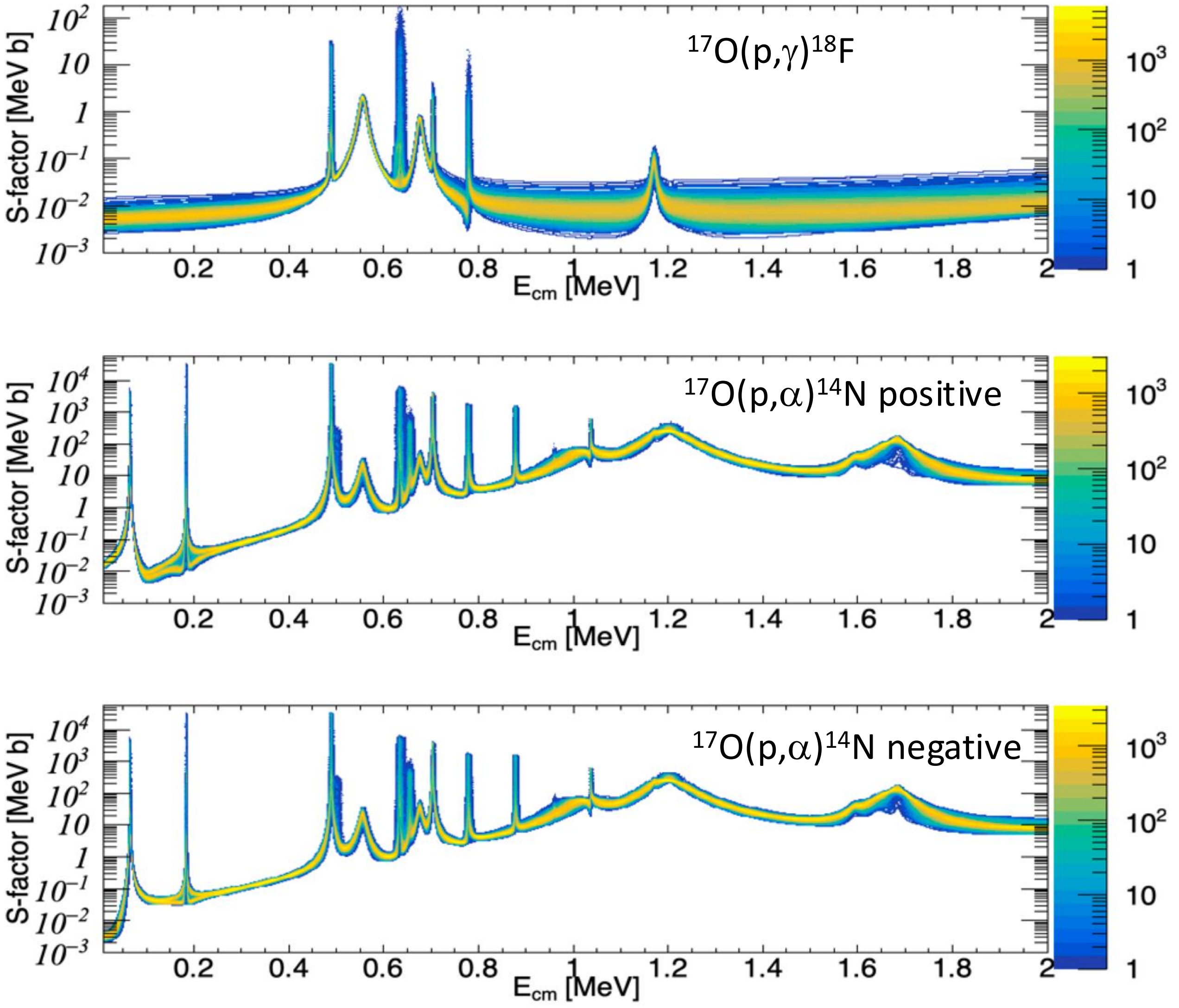

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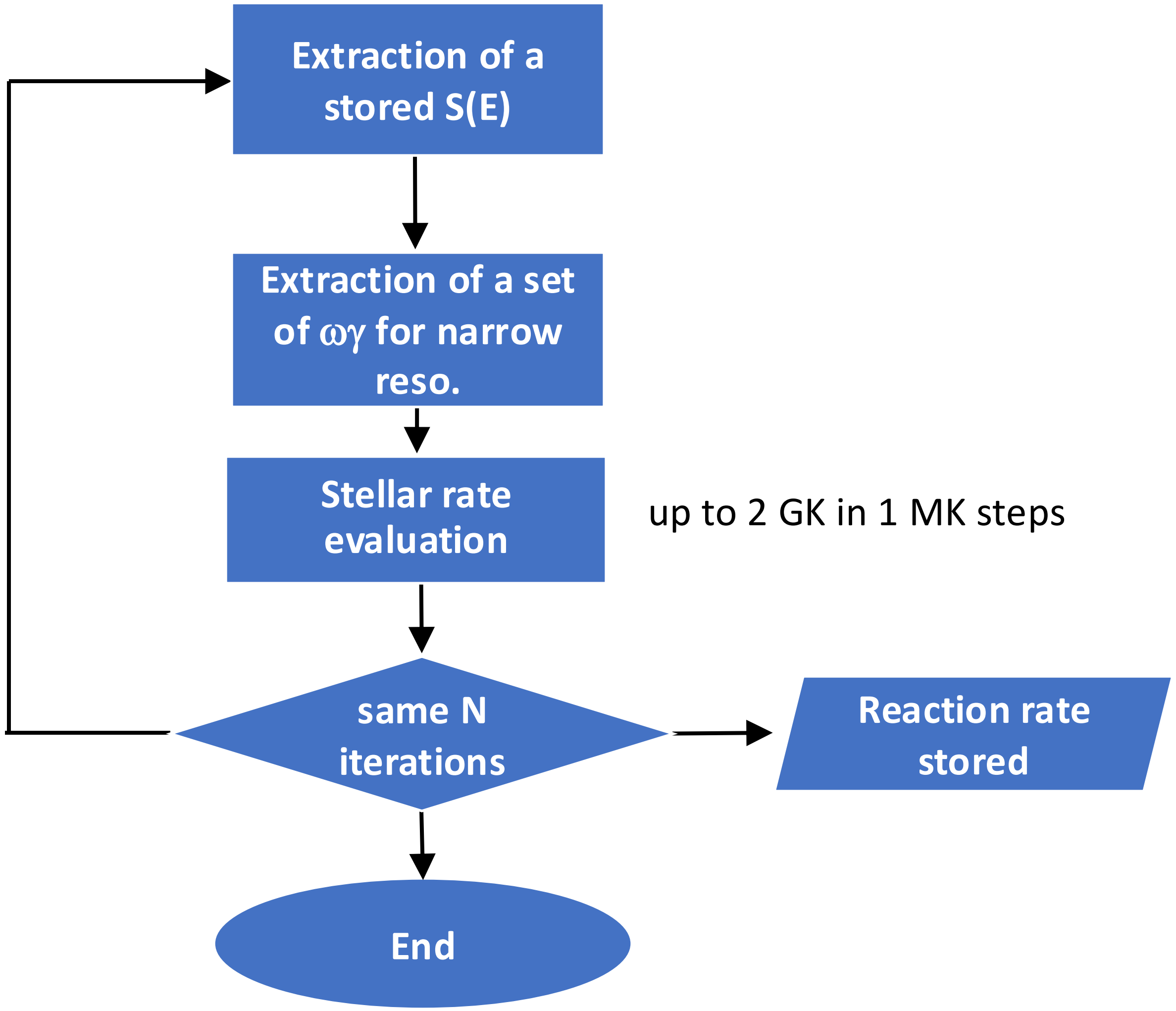

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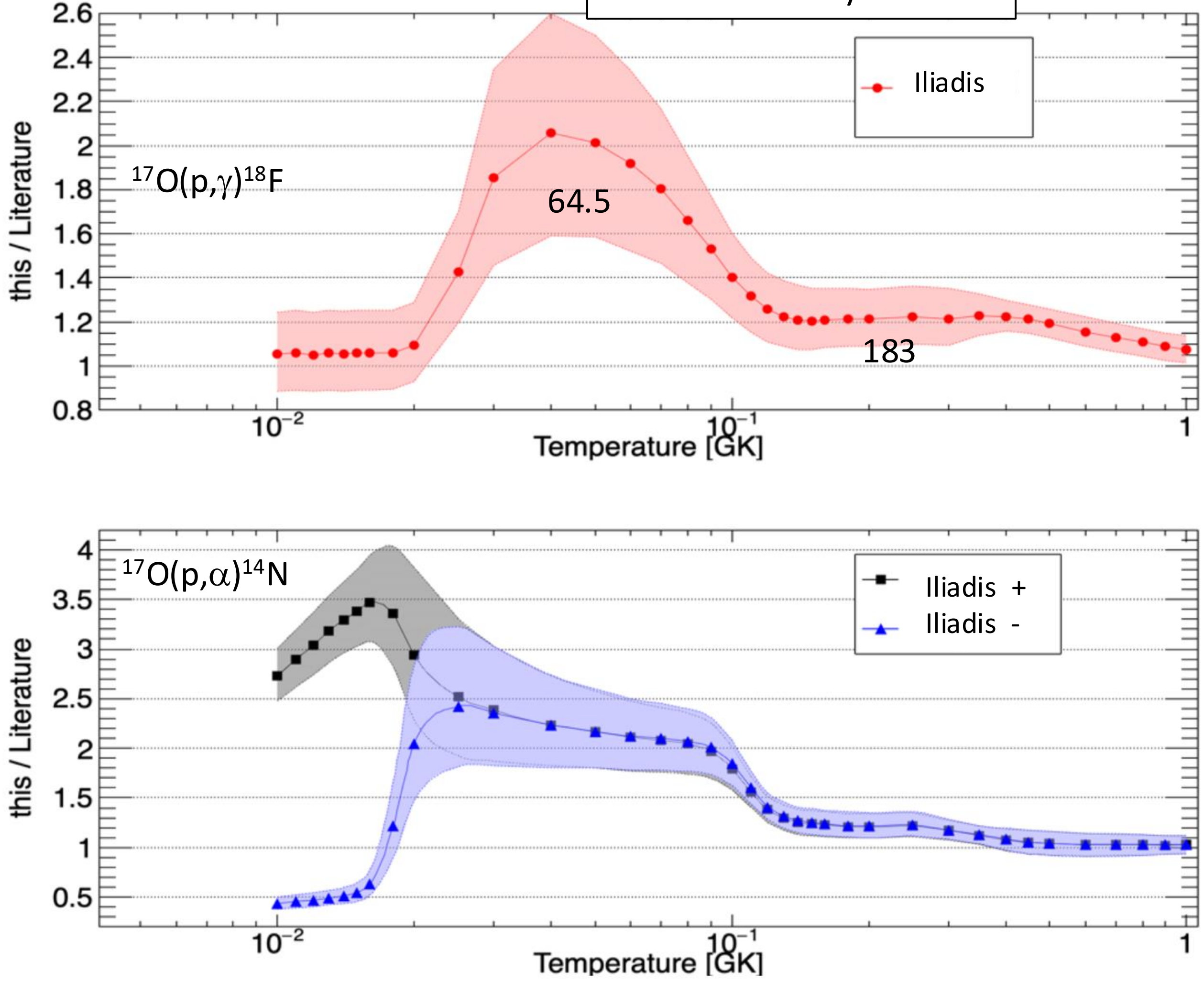
Comparison with Iliadis
2010 Nuclear Physics A841



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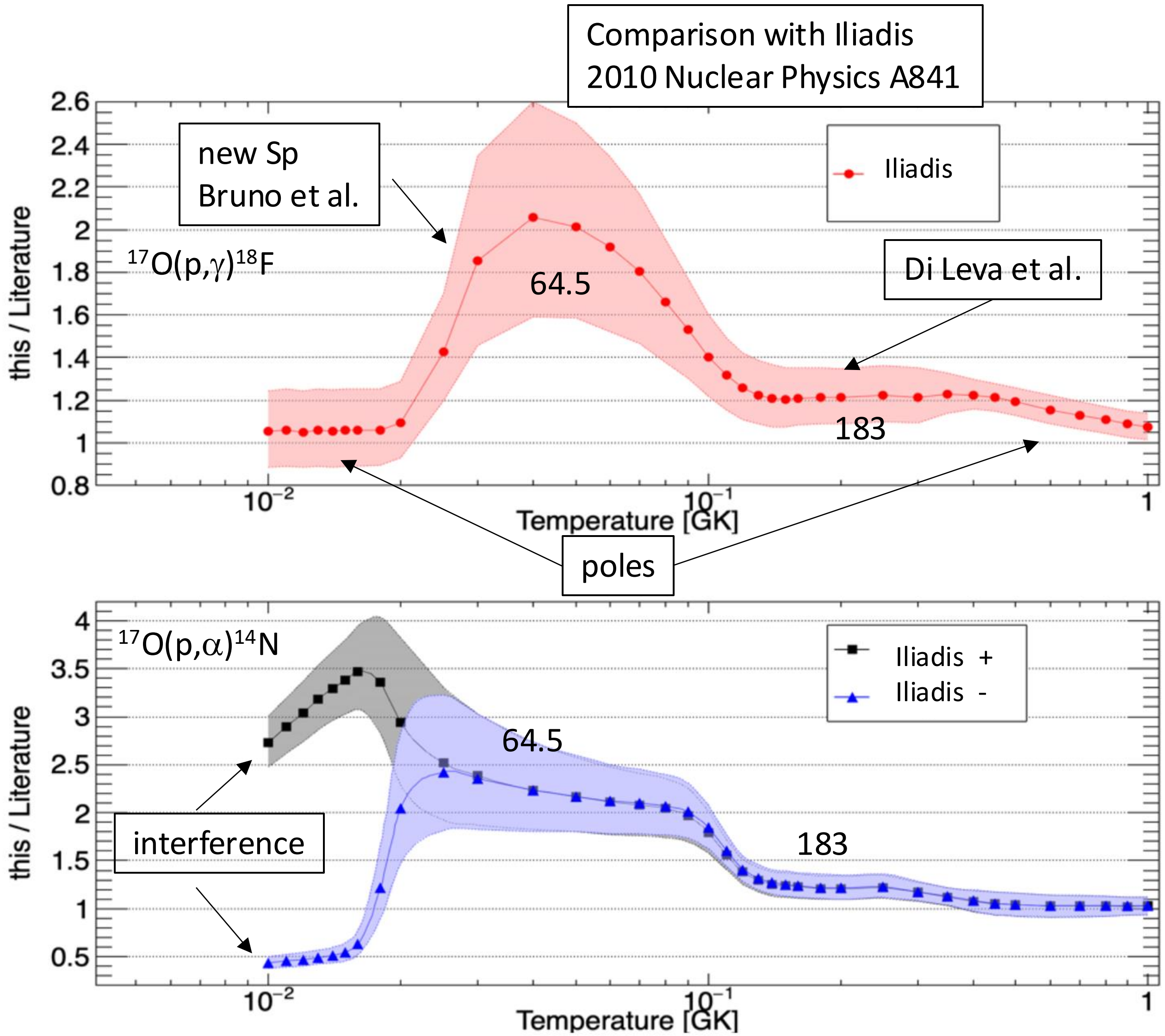

Outlooks

- astrophysical impact under evaluation, publication soon
- $^{14}N(p,\gamma)^{15}O$ - $^{15}N(p,\gamma)^{16}O$ - $^{17}O(p,\gamma)^{18}F$ - $^{17}O(p,\alpha)^{14}N$ - $^{18}O(p,\gamma)^{19}F$ - $^{18}O(p,\alpha)^{15}N$ $^{12}C(p, \gamma)$, $^{13}C(p, \gamma)$, $^{16}O(p, \gamma)$ –> in progress

complete — in progress — next future

Thank you for your attention!!!

The CNO LUNA Working Group: Carlo Broggini, Daniel Bemmerer, Carlo Gustavino, Axel Boeltzig, Paola Marigo, Antonio Caciolli, Andreas Best, Matthias Junker, Carlo Bruno, Marialuisa Aliotta, Antonino Di Leva, Alba Formicola, David Rapagnani, Maria Lugaro, Gianluca Imbriani, Oscar Straniero

Reaction Rate evaluation

$$N_A < \sigma v >= \frac{3.7318 \cdot 10^{10}}{T_9^{3/2} \mu_{01}^{-1/2}} \int E_6 \sigma(E_6) e^{-11.605 E_6/T_9} dE_6$$

R-Matrix cross section

$$N_A < \sigma v >= \frac{1.5399 \cdot 10^{11}}{T_9^{3/2} \mu_{01}^{-3/2}} \omega\gamma\, e^{-11.605 E_6/T_9}$$

Narrow Resonance approximation

Binning effects